Second Edition, 2000, Lattice Press, pp. xviii-xxi, 488, and 545) that was inadvertently omitted therefrom.

Remarks

If it is deemed helpful or beneficial to the efficient prosecution of the present application, the Examiner is invited to contact Applicant's undersigned representative by telephone.

Respectfully submitted,

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SILICON PROCESSING FOR THE VLSI ERA

VOLUME 1: PROCESS TECHNOLOGY

Second Edition

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Chapter 12
LITHOGRAPHY I:
OPTICAL PHOTORESIST MATERIALS and PROCESS TECHNOLOGY

Microcircuit fabrication requires precisely controlled quantities of impurities to be introduced into tiny regions of the silicon substrate. Subsequently these regions must be interconnected to create components and VLSI circuits. The patterns that define such regions are created by lithographic processes. That is, a layer of photoresist materials is first spin-coated onto the wafer substrate. Next, this resist is selectively exposed to a form of radiation, such as ultraviolet light, electrons, or x-rays. An exposure tool and mask are used to effect the desired selective exposure. The patterns in the resist are formed when the wafer undergoes a subsequent "development" step. The areas of resist remaining after development protect the substrate regions which they cover. Locations from which resist has been removed can be subjected to a variety subtractive (e.g., etching) or additive (e.g., ion implantation) processes that transfer the pattern onto the substrate surface. An advanced IC can have 20 or more masking layers. Approximately one-third of the total cost of semiconductor manufacturing can be attributed to microlithographic processing.

Two chapters of this text are devoted to the details of lithographic processing for ULSI. The first is concerned with the properties of photoresist materials and the resist processing technology utilized in ULSI fabrication. The discussion is restricted to resists exposed by optical (e.g., UV and DUV) radiation. The second chapter deals with the tools used to expose the resist. That is, optical aligning equipment and photomasks are described, as well as alternatives to optical lithography, including electron beam and x-ray patterning technology.

In general, users of resists are not overly concerned with the complexities of resist chemistry, but rather how well the resist will function in their process. The majority of the information in this chapter is presented with this focus. Photoresists have been used in the printing industry to make pre-coated lithographic printing plates for more than a century. In the 1920s photoresists found wide application in the printed circuit board industry. The semiconductor industry adapted this technique for wafer fabrication in the 1950s. By 1991 the semiconductor industry consumed about 2500 tons of photoresist per year, which represented a sales of around $220 million ($US). The selling price of photoresist in the late 1990's was about $900/gallon. In the early days of the IC industry there were a large number of resist suppliers. As the lithography process matured, the number of vendors consolidated, and by the end of the century a much smaller number remained. In the U.S. there are two resist vendors, Olin Microelectronic Materials (who purchased McDermitt, Ciba-Geigy and KTI {Kodak}), and the Shipley Company. Foreign suppliers include Clariant Corp. (formerly AZ Electronic Materials), Tokyo Ohka Kogyo, and JSR Microelectronics.

Chapter 13
LITHOGRAPHY II: OPTICAL ALIGNERS and PHOTOMASKS

In the previous chapter the material properties of photoresists and their processing technology were covered. This chapter will describe the remainder of the topics involved in the microlithographic process of transferring patterns to silicon wafers, including: a) a brief introduction to the optical science involving the formation of aerial images of the circuit patterns on the resist surface; b) the equipment used to project these images onto the wafer surface (the so-called *aligners* or *printers*); c) the pattern transfer tools that contain the patterns to be printed onto the photoresist-coated wafers (the photomasks and reticles); and 4) non-optical microlithographic technologies that are being investigated as replacements for optical lithography.

Before beginning the discussion on optics, however, it is useful to identify the key issues of microlithography hardware. The most important characteristics of the machines and masks used to project the patterns onto wafer surfaces are the following: a) resolution; b) pattern registration capability (alignment and overlay); c) dimensional control; and d) throughput.

In general, the term *resolution* of an *optical system* describes it's ability to print a minimum feature size. Specifically, the *minimum resolution* of a microlithographic printing machine will be referred to as the dimension of minimum linewidth or space that the machine can adequately print (or *resolve*). The ability to form IC features of such minimum dimensions also depends on the photoresist and the etching technology. The topic of resolution of optical systems is dealt with more thoroughly in the section on *Optics of Microlithography*, but it is important to emphasize that *high resolution* is usually the most sought after property of an aligner. The subject of resolution of optical lithography systems will be briefly discussed here, admittedly using some terms that are not defined until later.

Consider the case of an isolated transparent line on an opaque mask. The intensity of the light projected onto the wafer surface (as a function of the normalized distance from the center of the line) is shown in Fig. 13-1 for: 1) the ideal case; and 2) the actual case for three different line widths (i.e., 0.35 μm, 0.25 μm, and 0.18 μm) when imaged by a specific optical system containing a perfect (distortion-free) lens. In this example, the NA of the lens is 0.5, the illuminating wavelength is 0.248 μm, and the system has a partial coherence of $\sigma = 0.6$. Even though all of these terms have not yet been defined, what is important to note is that for any specific optical system, as the dimension of the line gets smaller, there is a degradation of the